Constellation-X and the Growth of Massive Black Holes at High Redshift

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1. Introduction

Our understanding of the growth and evolution of massive black holes has undergone a revolution over the last few years. It now seems likely that the development of black holes and galaxies are intimately connected, possibly due to accretion-related outflows that regulate star formation (e.g., Silk & Rees 1998; King & Pounds 2003). This growth appears to undergo a curious evolutionary trend whereby black holes are built-up via accretion with the most massive black holes forming first, a process often referred to as cosmic downsizing (e.g., Cowie et al. 2003; Marconi et al. 2004). The number density of these accreting massive black holes [i.e., Active Galactic Nuclei (AGN)] changes dramatically over the history of the Universe, however, there is no clear observational evidence that AGNs of a given luminosity undergo substantial changes in their underlying accretion processes (e.g., Vignali, Brandt & Schneider 2003). Furthermore, it is apparent that a large (likely luminosity-dependent) fraction of AGNs are obscured at optical wavelengths but are detectable at hard X-ray energies (e.g., Mainieri et al. 2002; Ueda et al. 2003; Barger et al. 2005). These obscured sources are suspected to be the dominant AGN population in the Universe (outnumbering unobscured AGNs by factors of 3–10) and contribute the bulk of the cosmic X-ray background (CXRB) radiation.

With its high-resolution ($R \gtrsim$ 500–1000) X-ray spectrometers, $\gtrsim$ 100 times the collecting area of *Chandra* and *XMM-Newton* at 0.25–10 keV, and crucial sensitivity at hard (10–40 keV) X-ray energies, *Constellation-X* will allow astronomers to probe the growth of black holes in the high-redshift Universe with unprecedented precision; see Figure 1.

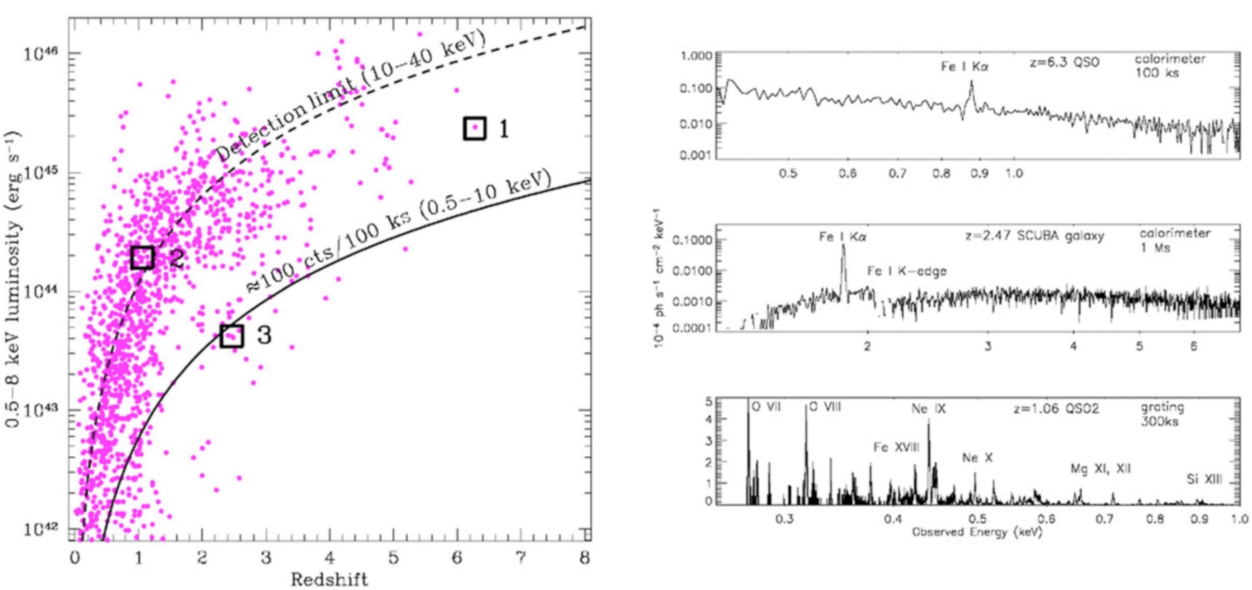

Figure 1 ***Left****:* X-ray luminosity versus redshift for some potential *Constellation-X* targets. The compiled sources are a heterogeneous combination of different samples in the literature, including wide and deep *Chandra* blank-field observations and X-ray targeted AGNs. The sources above the solid line can be studied by *Constellation-X* in the 0.5–10 keV band in < 100 ks exposures. The sources above the dashed line can be detected by *Constellation-X* in the 10–40 keV band. An X-ray spectral slope of Γ=2.0 was assumed when converting from the 0.5–8.0 keV band to the *Constellation-X* bands. ***Right***: Simulated spectra demonstrating the capabilities of *Constellation-X* for the three

highlighted sources (1; *top*) a z = 6.3 quasar, (2; *middle*) a z = 2.47 Compton-thick AGN in a submillimeter-bright star-forming galaxy, and (3; *bottom*) a z = 1.06 obscured quasar. Interesting spectral features are highlighted.

Constellation-X will study $z \approx 1$ AGNs with the detail only currently possible for the ~10 brightest local AGN (such as NGC 5548); luminous $z > 6$ quasars will be more accessible to *Constellation-X* at high spectral resolution than simgt z 1 quasars are to C*handra* and *XMM-Newton* at much lower spectral resolution. Coupled with current and future radio through to hard X-ray data, these observations will provide comprehensive probes of the physics of accretion around high-redshift massive black holes. The large-scale AGN outflows (in absorption and emission) that likely regulate star formation in massive galaxies will be studied in detail, providing estimates of mass and energy outflow rates and chemical enrichment/heating of the IGM. The energetics and demographics of high-redshift obscured AGNs will be quantified and many luminous Compton-thick AGNs will be revealed with *Constellation-X*'s high-energy sensitivity out to 40 keV.

2. Physics of the Central Engine

Our basic picture of an AGN is one where an accretion disk is funneling material into a supermassive black hole. AGNs emit X-rays as a result of Compton upscattering of ultraviolet photons from the accretion disk as they pass through a bath of high energy electrons in the accretion-disk corona. This X-ray emission provides a unique window on the environment closest to the accreting black hole (to $R_g \approx$ 1.2) that is inaccessible at other wavelengths". *Constellation-X* will provide X-ray spectroscopy of AGNs down to 0.5–8 keV flux levels of $\approx 10^{-15}$ $ergs^{-1}$ cm^{-2} permitting constraints on the continuum shape, absorption, recombination emission, fluorescent iron K line emission, Compton reflection, and variability of accreting black holes out to and beyond z = 6; see Figures 1 and 2. At high redshift this emission gets shifted to lower observed energies, providing measurements at energies that may otherwise be inaccessible for studies of local AGNs.

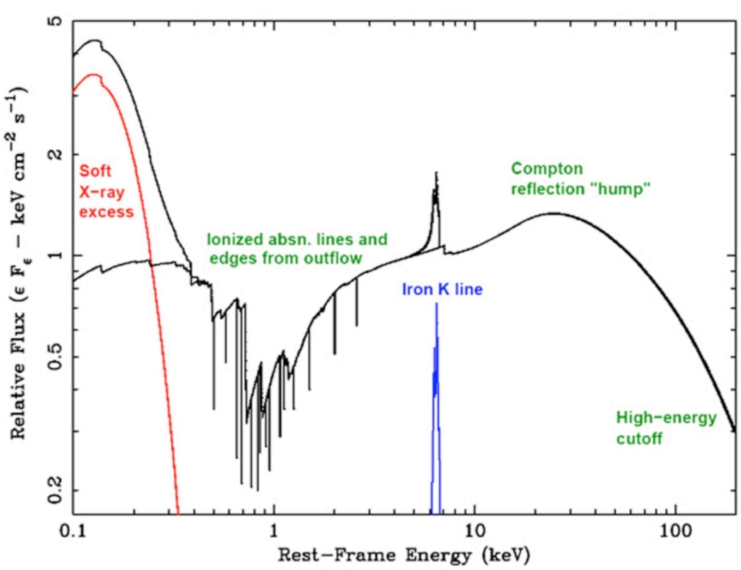

Figure 2: Typical soft X-ray through to hard X-ray spectral energy distribution of an AGN, showing the variety of spectral features that *Constellation-X*'s resolution, throughput, and energy coverage will reveal. The broad *Constellation-X* bandpass covers an energy range equivalent to the far-ultraviolet — mid-infrared band at longer wavelengths. At z = 0, *Constellation-X* will sample 0.25–40 keV; at z = 6, *Constellation-X* will sample 1.75–280 keV.

Our understanding of the X-ray emission from high-redshift AGNs has advanced rapidly since the launches of *Chandra* and *XMM-Newton* and the advent of wide-field optical surveys (see Brandt et al. 2005 for a review); for example, the number of X-ray detections at $z > 4$ has increased from 6 in 2000 to

$\approx$ 100 today. No significant changes in the X-ray emission properties of AGNs at high and low redshift have yet been found, suggesting that the accretion-disk environment of AGNs are insensitive to the dramatic evolution on larger scales that occurred over the last 12 billion years of cosmic history (e.g., Vignali, Brandt, & Schneider 2003; Strateva et al. 2005). However, our current *Chandra* and *XMM-Newton* detections of high-z AGNs are just that – detections. As a result of comparatively poor photon statistics we do not have sufficient data to study their detailed properties; existing studies have generally been restricted to broad comparisons of their spectral energy distributions (SEDs). *Constellation-X* will allow astronomers to take these analyses one step further, permitting comparisons of X-ray spectral features and emission regions and therefore providing direct astrophysical insight into the evolution of the environment around accreting massive black holes; see Figure 1.

Relativistically broadened iron Kα emission provides information on the physical conditions in the immediate vicinity of the black hole. A number of local AGNs have shown relativistic iron Kα emission, permitting measurements of the black-hole spin and environment of the inner accretion disk (e.g., Reynolds & Nowak 2003). By comparison, luminous high-redshift AGN do not typically show these features (the weakness of iron Kα in luminous sources is known as the "X-ray Baldwin effect"); however, the stacked X-ray spectra of X-ray faint high-redshift AGN appear to show the signature of relativistically broadened iron Kα emission on average (Streblyanska et al. 2005). *Constellation-X* has the sensitivity to identify and study iron Kα emission lines in individual high-redshift AGN, providing insight into the conditions necessary to produce iron K-alpha emission and its evolution with redshift.

Beyond the iron Kα emission line and the reflection component (which peaks at 20–30 keV) the hard X-ray spectra of AGN are dominated by the Compton upscattered component. Since there are currently no reliable measures of the high-energy Compton cutoff in quasars, the sensitive 10–40 keV hard energy coverage of *Constellation-X* will provide new insights into our understanding of the state and structure of the X-ray emitting accretion-disk coronae (e.g., Sobolewska, Siemiginowska, & Zycki 2004; Zdziarski & Gierlinski 2004). For high-redshift quasars where we can probe rest-frame energies of ~100-300 keV (and perhaps as high as 600 keV), we can expect to see the high-energy cutoff (50–200 keV) in some cases, thus allowing a determination of the electron temperature and optical depth of the Comptonizing plasma. This information is key to our understanding of the geometry of the corona, and, in turn, to the modeling of the accretion disk and disk-wind emission.

These studies of the central engine of high-redshift AGNs benefit significantly from *Constellation-X*'s hard energy coverage, which for the highest redshift quasars currently known will probe rest frame energies higher than 240 keV. However, the background must be lower than the expected 10–40 keV fluxes of typical z $\approx$ 4 quasars of $\approx 10^{-14}$ –10^{-15} erg s^{-1}cm^{-2}. With sufficiently low background and spatial resolution better than 5″ HPD it may be possible for *Constellation-X* to *detect* and cross-identify AGN at even higher redshifts ($z > 8$). Response at low energies is also important as crucial spectral features move with redshift; for example, iron Kα is observed at $\approx$ 1 keV at $z \approx 5$ and the presence of moderate absorption (i.e., $N_H \lesssim 2 \times 10^{22}$ cm^{-2}) becomes increasingly difficult to identify at high redshift without good low-energy response.

3. Accretion-disk Outflows and their Role in Galaxy Evolution

The study of AGNs has undergone a paradigm shift in recent years with considerable emphasis being placed on accretion-related outflows (e.g., Murray et al. 1995; Proga, Stone, & Kallman 2000). Over cosmic time a significant fraction of the energy from massive black-hole accretion could be converted into kinetic energy by large-scale outflows, affecting the host galaxy by triggering star formation [e.g., shocking and compressing the interstellar medium (ISM)], or perhaps even shutting it down (e.g., clearing gas from the host; Fabian 1999). Indeed, current large scale-structure simulations require the presence of AGN "feedback" to regulate the growth of massive galaxies (e.g., De Lucia et al. 2004). These high-velocity winds and jets are also an efficient means of distributing high-metallicity gas into the IGM, and could be important for disrupting cooling flows in the centers of massive galaxies and clusters. X-rays provide penetrating probes of all of the material in an outflow, from cool dust through to highly ionized gas, and only high-velocity X-ray photoionized outflows carry enough mass and kinetic energy to significantly affect the ISM and IGM. *Constellation-X* spectroscopy will provide the crucial information to quantify accretion-related mass-outflow rates and metallicities to determine their importance in massive galaxy evolution.

High spectral resolution studies of a few local AGN with *Chandra* and *XMM-Newton* have uncovered a forest of ionized absorption lines, indicating highly ionized outflows projected against the bright nucleus (e.g., Kaastra et al. 2000; Kaspi et al. 2002). More extreme absorption has been detected in quasars (e.g., Pounds et al. 2003; Chartas et al. 2003). However, *Chandra* and *XMM-Newton* only have the sensitivity to obtain low-resolution spectra of quasars (R=10–40 at 1–6 keV). *Constellation-X*'s large effective area and high spectral resolution will permit detailed constraints on accretion-related outflows at $z \approx$ 1–3, allowing their effect on the evolution of massive galaxies to be directly quantified. Figure 3 illustrates the potential of *Constellation-X* spectroscopy to reveal complex outflow structure in luminous high-redshift quasars for the first time. In the iron emission-line region (rest-frame energies > 6.4 keV), in-depth investigations of thick outflows will be readily accessible. However, the low abundance of iron and fainter continuum will render less massive (and perhaps more typical) outflows invisible in this regime, thus the spectral region at rest-frame energies < 2 keV where lighter elements dominate is also crucial.

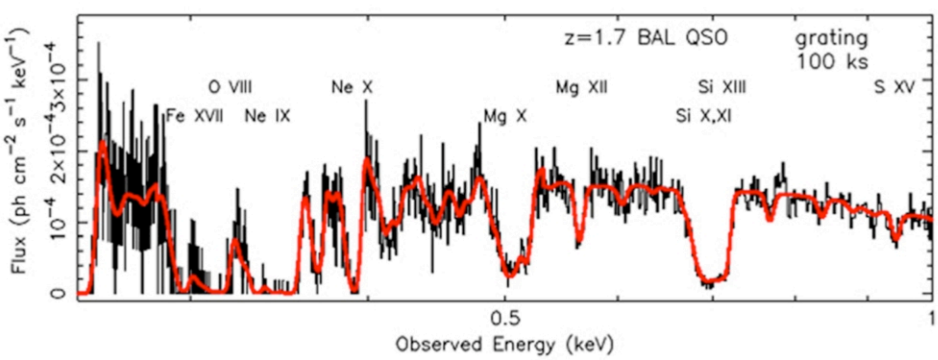

Figure 3: 100 ks *Constellation-X* simulation of a z = 1.7 quasar with an ionized, high velocity outflow and a flux comparable to PG1115+080 (Chartas et al. 2003). Substantial effective area at low energies (0.2–1 keV) is essential; crucial spectral features such as the resonance lines and edges of highly ionized O, Ne, Mg, and Si (E = 0.5–2.7 keV) move to lower energies with redshift. These spectral features provide important constraints on the physical conditions in moderate column density gas.

In obscured AGNs the direct continuum from the central engine is hidden, thus hiding absorption signatures of outflows, but the outflows can still be seen as a forest of soft X-ray emission lines (e.g., Sako et al. 2000; Ogle et al. 2000). These emission-line spectra are as rich in diagnostic power as absorption-line spectra, and since obscured AGNs are more numerous than unobscured AGNs a larger fraction of the overall outflow energy might be present in emission-line outflows. Only *Constellation-X* has the sensitivity and spectral resolution to observe emission-line dominated outflows over a wide range in redshift and luminosity and thus, for the first time, obtain a cosmic census of the mechanical energy from AGN activity. Emission from oxygen through to iron can be used to measure the elemental abundances of high-redshift quasars, an essential constraint on early star formation. The column density of gas determines the ratio of recombination line strengths, while the temperature of the gas sets the width of the recombination continuum. The Doppler shifts and widths of emission lines yield the outflow and turbulent velocities, and together with the column densities, ionization parameter, and covering fraction, enables measurement of the kinematic power – the fundamental quantity for determining the impact of the AGN on its host galaxy and the IGM.

Each high-quality *Constellation-X* spectrum will reveal a wealth of physics integral to understanding the role of AGN feedback in galaxy formation as well as the interplay between massive black-hole accretion and outflow. Extracting these physical diagnostics requires rest-frame spectral resolution of at least R~ 600 (250 km s^{-1} at $z = 1$) and high effective area (>1000 cm^2) at energies down to 0.25 keV. With X-ray gratings spectroscopy, the constant $\Delta\lambda$ resolution allows redshift to effectively improve the spectral resolution across a given transition by a factor of $1 + z$.

4. The Energetics and Role of Obscured Accretion

The CXRB primarily probes the integrated accretion activity of the Universe over all of cosmic time. The deepest C*handra* and *XMM-Newton* surveys have directly resolved ≈ 90% of the 0.5–6 keV CXRB and ≈ 50% of the 6–12 keV CXRB (Worsley et al. 2005), uncovering an order of magnitude higher AGN source density than found at other wavelengths (e.g., ≈ 7200 deg^{-2}; Bauer et al. 2004). Although it is apparent that many of these sources are previously undiscovered obscured AGN at $z < 3$ (e.g., Barger et al. 2002; Wilkes et al. 2002), their individual X-ray spectra, and therefore the properties of the primary X-ray emission, cannot be comprehensively characterized by C*handra* and *XMM-Newton*. The black holes in many of the $z > 1$ obscured AGNs are likely to be undergoing a high-accretion rate growth phase (e.g., Marconi et al. 2004; Alexander et al. 2005) and *Constellation-X* will provide unique information on their environment and energetics.

The significant improvements in collecting area, spectral resolution, and high-energy bandpass that *Constellation-X* will bring over previous X-ray observatories will provide the first detailed understanding of the central engines of individual high-redshift obscured AGN; see Figure 1. This will lead to a greater understanding of the energetic output from obscured black-hole growth and provide tighter constraints on the ratio of obscured to unobscured accretion activity. Moderate-quality X-ray spectra of z ≈ 1–3 luminous obscured quasars will be possible in ≈ 100 ks exposures; however, X-ray spectra of more typical, and more heavily obscured AGNs, may require significantly longer exposures (e.g., ~1 Ms). These spectra will be of sufficient quality to constrain absorbing column densities, quantify the properties of any iron line emission, and determine the intrinsic X-ray luminosity of the AGN.. Many of the X-ray sources detected in deep C*handra* and *XMM-Newton* observations are X-ray bright but have counterparts too faint for optical spectroscopic redshift determination (e.g., Alexander et al. 2001; Barger et al. 2003). The identification of iron-K emission lines via *Constellation-X* spectroscopy may provide the most viable way to determine redshifts for these sources. In addition to the expected obscuration and outflow signatures expected in $z > 1$ obscured AGNs (see Figure 1), many are also likely to be undergoing vigorous star formation. For a $z \approx 1$ obscured quasar with the same star-formation characteristics as NGC 6240, *Constellation-X* would be able to obtain an X-ray spectrum of sufficient quality to be able to determine key star-formation properties in a typical 100 ks exposure. For example, this should allow for the detection of a star-formation related outflow with velocity of order 300 kms^{-1} and α process abundance enhancement relative to iron of a factor of two. Both of these would provide strong evidence for the enrichment of the IGM by starburst activity and the role of starburst feedback on galaxy formation.

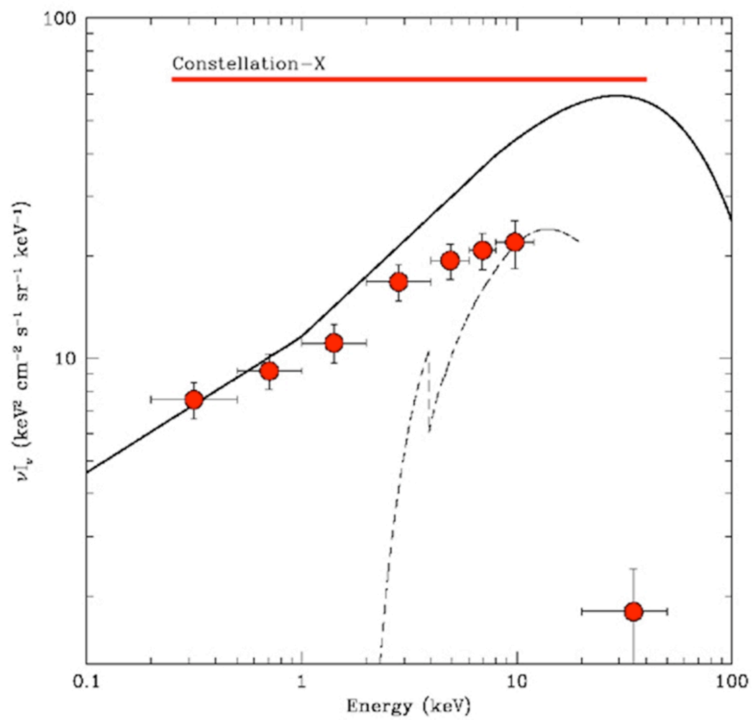

Figure 4: Energy density of the Cosmic X-ray Background (CXRB; solid line). The solid circles show the fraction of the CXRB resolved into sources by the deep *XMM-Newton* observation of the Lockman Hole up to 12 keV (Worsley et al. 2005) and at 20–50 keV by deep *INTEGRAL* observations of the Coma cluster (Krivonos et al. 2004). *Constellation-X* will directly observe the CXRB at the energy at which it peaks (≈ 30 keV) and will be several orders of magnitude more sensitive than previous missions. The dashed curve shows a moderate redshift (z = 0.8), obscured AGN (N_H = 4.5 x 10^{23} cm^{-2}); a large population of similar and more heavily obscured sources are most likely responsible for the 30 keV peak of the CXRB.

The deepest >10 keV observations of the Universe have only resolved ≈ 3% of the CXRB at its ≈ 20–50 keV peak (Krivonos et al. 2004); see Figure 4. The undiscovered sources that contribute to the majority of the >10 keV background are likely to be heavily obscured, sometimes Compton thick, AGN and many may not be detectable at <10 keV; see Figure 1 for sensitivity constraints. With more than an order of magnitude improvement in both spectral and angular resolution, and a significant advance in collecting area, *Constellation-X* will be ≈ 100 times more sensitive than *INTEGRAL* at 40 keV, and will resolve approximately half of the CXRB at 10-40 keV.

Much of the potential high-redshift obscured AGN science with *Constellation-X* will require long exposures (>100 ks). The largest possible field of view will provide the best scientific return for these long exposures, enabling X-ray detections and X-ray spectra for many sources to be obtained in one *Constellation-X* observation. This could be achieved by expanding the size of the calorimeter or expanding the field of view using CCDs, which could also be used serendipitously for faint survey science. Ideally, the field of view of the HXT and SXT would be matched. Minimizing the background level will maximize the scientific return of the HXT, permitting more sensitive 10–40 keV observations and resolving a larger fraction of the CXRB.

REFERENCES

Alexander, D.M., Brandt, W.N., Hornschemeier, A.E., Garmire, G.P., Schneider, D.P., Bauer, F.E., & Griffiths, R.E., 2001, AJ, 122, 2156

Alexander, D.M., Smail, I., Bauer, F.E., Chapman, S.C., Blain, A.W., Brandt, W.N., & Ivison, R.J. 2005, Nature, submitted

Barger, A.J., et al. 2003, AJ, 126, 632

Barger, A.J., Cowie, L.L., Mushotzky, R.F., & Richards, E.A. 2001, AJ, 121, 662

Barger, A.J., Cowie, L.L., Brandt, W.N., Capak, P., Garmire, G.P., Hornschemeier, A.E., Steffen, A.T., & Wehner, E.H. 2003, AJ, 124, 1839

Barger, A.J, et al. 2005, AJ, in press (astro-ph/0410527)

Brandt, W.N., et al. 2005, astro-ph/0411355

Chartas, G., Brandt, W. N., & Gallagher, S. C., 2003, ApJ, 595, 85

Cowie, L.L., Barger, A.J., Bautz, M.W., Brandt, W. N., & Garmire, G.P. 2003, ApJ, 584, L57

De Lucia, G., Kauffmann, G., & White, S.D.M. 2004, MNRAS, 349, 1101

Fabian, A.C. 1999, MNRAS, 308, L39

Kaastra, J. S., Mewe, R., Liedahl, D. A., Komossa, S., & Brinkman, A. C. 2000, A&A, 354, L83

Kaspi, S. et al. 2002, ApJ, 574, 643

King, A.R. & Pounds, K.A. 2003, MNRAS, 345, 657

Krivonos, R. et al. 2005, ApJ, submitted (astro-ph/0409093)

Mainieri, V., Bergeron, J., Hasinger, G., Lehmann, I., Rosati, P., Schmidt, M., Szokoly, G., & Della Ceca, R. 2002, A & A, 393, 425

Marconi, A., Risaliti, G., Gilli, R., Hunt, L.K., Maiolino, R., & Salvati, M. 2004, MNRAS, 351, 169

Murray, N., Chiang, J., Grossman, S.A., & Voit, G.M. 1995, ApJ, 451, 498

Ogle, P. M., Marshall, H. L., Lee, J. C., & Canizares, C. R., 2000, ApJ, 545, 81

Pounds, K. A., Reeves, J. N., King, A. R., Page, K. L., O'Brien, P. T., & Turner, M. J. L., 2003, MNRAS, 345, 705

Proga, D., Stone, J.M., & Kallman, T.R. 2000, ApJ, 543, 686

Reynolds, C.S. & Nowak, M.A. 2003, Phys. Rep., 377, 389

Sako, Masao, Kahn, Steven M., Paerels, F., & Liedahl, D. A., 2000, ApJ, 543, L115

Silk, J. & Rees, M.J. 1998, A&A, 331, L1

Sobolewska, M.A., Siemiginowska, A., & Zycki, P.T. 2004, ApJ, 608, 80

Strateva, I. et al. 2005, AJ, submitted

Streblyanska, A., et al. 2005, A&A, submitted (astro-ph/0411340)

Ueda, Y., Akiyama, M., Ohta, K., & Miyaji, T. 2003, ApJ, 598, 886

Vignali, C., Brandt, W.N., & Schneider, D.P. 2003, AJ, 125, 433

Wilkes, B.J., Schmidt, G.D., Cutri, R.M., Ghosh, H., Hines, D.C., Nelson, B., & Smith, P.S. 2002, ApJ, 564, L65

Worsley et al. 2005, astro-ph/0412266 MNRAS accepted

Zdziarski, A.A. & Gierlinski, M. 2004, Progress of Theoretical Physics Supplement, 155, 99